

AGROMETEOROLOGICAL METHODS  
FOR FORECASTING AND ESTIMATING CROP YIELD

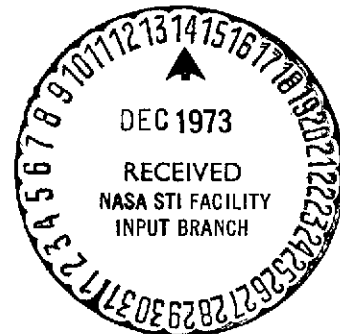
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AGROMETEOROLOGICAL METHODS  
FOR FORECASTING AND ESTIMATING CROP YIELD<sup>†</sup>

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The estimation of the climatic assurance of crop yield, especially of introduced varieties (hybrids), and forecasting the crop in the current year on the basis of agrometeorological data has great practical significance for the national economy.

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The development of numerical methods of agricultural appraisal of climate and of agrometeorological forecasting has a comparatively short history, since their basis is the accumulation of an immense amount of observational data from a network of meteorological stations over the period of germination and growth of crops, combined with record keeping of meteorological factors, soil moisture, and the level of agricultural technology. In the past decade this problem has been attracting an ever-widening circle of scientists in many countries, as indeed is evidenced by the program of the present symposium.

In the USSR the first agrometeorological forecasts of the yield of staple agricultural crops were made in 1964, and since then they have been widely used in farming practice.

The scientific basis of agrometeorological forecasting is the discovery by agrometeorologists of the dependence of the germination, development, and maturation of agricultural plants on meteorological factors, the dynamics of soil moisture supply, and the particulars of cultivation. These relations were determined starting from assumptions about the essentiality of a plant's life factors and the lesser significance of their environment. It then follows that the most important life

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factors -- air, light, heat, moisture, soil fertility -- mainly determine the processes of crop maturation, whereas the remaining factors are corrective. Also, in the selection of predictors for forecasting yield, one must take into account the temporal variability of the factors.

It is well known that air composition and soil fertility, the most important of the life factors, have little variability from year to year by comparison with the considerable fluctuations of air temperature or moisture supply, which determine fluctuations in yield in regions with inadequate or unsteady moistness. Thus an increase in soil moisture because of bulk application of fertilizer is only a corrective factor, the effectiveness of which is determined to a considerable degree by meteorological conditions. As regards air composition, only the amount of water vapor (humidity) is characterized by large variability with time and place, and is a noticeable corrective factor during the period of ripening.

Other meteorological factors can emerge as corrective only in particular cases.

The processing of routine agrometeorological observations has as an objective the determination of basic predictors for forecasting yield. Using statistical methods, matrices of correlation coefficients and correlation ratios are calculated by ECM (electronic calculating machine). In doing this one takes into account that in the determination of coherence of any factor with yield, the phase of its influence on the crop during growth must be specified.

As early as the 19th century P. I. Brounov and subsequently 73 others laid down conditions concerning critical phases in the development of plants as regards moisture. It is now established

that the response of plants varies with meteorological factors depending on their stage of development.

As for the establishment of the number of spikelets in an ear of spring wheat, the supply of available moisture and the air temperature affect stages III-IV of organogenesis (stages of organogenesis are designated in accordance with the classification of F. M. Kuperman, USSR), but the quantity of grain in the ear for the same number of spikelets varies almost by a factor of 2 depending on the moisture supply in stages V-VI. The grain content of ears of corn, as our work has shown (Chirkov, 1961), can drop to 40% of the possible content for a given variety (hybrid), depending on moisture supply and air temperature. That is why one must take into account in working out matrices of correlation coefficients the phase of influence of the meteorological factors, considering their effect on the crop not only for the growing period as a whole, but also for particular intermediate periods or stages of organogenesis. Thus in a matrix compiled for medium-late varieties and hybrids of corn, the analysis of coherence of the yield with agrometeorological factors was carried out by phases: seedling to 10 blades; 11 blades to formation of the panicle; formation of the panicle to appearance of cob fibers; flowering to milky ripeness (Yu. I. Chirkov, 1966).

A similar analysis was carried out for the variety of winter wheat Bezostaya I (E. S. Ulanova, 1971) by the phases: resumption of growth to emergence of stalk; emergence of stalk to ear formation; ear formation to milky ripeness; milky to waxen ripeness. Also taken was the more inclusive period: resumption of growth to waxy ripeness. Of a number of factors affecting the yield, the following were chosen: duration of the intermediate phase, supply of available soil moisture in

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the spring and by phase of development at depths 0-20, 0-50, 0-100 cm, precipitation amount by intermediate phases, average air temperature, supply of available moisture averaged over the phase, number of days with precipitation, total evaporation, and in addition indicators of the structure of the crop; the number of stalks per  $m^2$  (from the phase of ear formation, the number of spike-bearing stems), height of the plants, the number of developed spikelets per ear, the quantity of grain in the ear, and the weight of 1000 kernels.

In the matrices for corn there are included, besides those indicators, the coherence of the yield with the humidity deficit, the aggregation of effective temperatures from 3rd blade to milky ripeness, and also, for specific corn, the structural features of the crop (average number of cobs on one plant, the height of the plants at formation of the panicle, the area of leaf surface per hectare of planting at the time of flowering).

Matrices were calculated for correlation coefficients and correlation ratios. Comparison indicates that the coherence of yield with agrometeorological factors can be evaluated only by correlation ratios, inasmuch as those associations have in the majority of cases a curvilinear character.

According to the investigations of E. S. Ulanova into conditions in the dark-colored soil zones, the closest relations of wheat yield are observed with the number of stems in the spring ( $\eta = 0.79$ ), in the phase of emergence of the stalk ( $\eta = 0.79$ ), and also with the number of ear-bearing stems in the flowering phase ( $\eta = 0.72$ ) and in the phase of waxy ripeness ( $\eta = 0.78$ ). The second most closely related factor is the height of the winter wheat plants starting from the flowering phase ( $\eta = 0.69$  to  $0.73$ ). The tertiary factors are the supply of available moisture in the soil layer from 0 to 100 cm during the 10 days following the resumption of growth

in the spring and in the decade of mass onset of the phase, "emergence of stalk" ( $\eta = 0.67$  to  $0.68$ ).

The dependence of the yield on the supply of available moisture drops in the following phases, since in the preceding period the moisture supply is of basic importance in the establishment of the number of spikelets in an ear. /5

Correlation ratios connecting the yield with the weight of 1000 kernels, with the duration of the intermediate phases, with the number of days with precipitation for the growing period to waxy ripeness, and for the period from milky to waxy ripeness, and also with the air temperature averaged from emergence of stalk to flowering are found to be within the range of  $0.62$  to  $0.50$ . The magnitude of the correlation ratios relating to total evaporation, precipitation amount, and average air temperature for the different intermediate phases was less than  $0.5$ .

Hence the equations for the agrometeorological forecast of the yield of winter wheat must primarily contain the basic factors which determine maturation of the crop: moisture supply, the number of stems per  $m^2$  in spring or in the phase of emergence of the stalk, and, for the forecast prepared in the flowering phase, the number of stems with an ear and the height of the plants. Accounting for only the indicated factors gives a high confidence level to the equations ( $80\%$ ), and with the inclusion of secondary predictors their confidence level rises to  $90\%$ .

Through calculations by ECM, Ulanova obtained a series of prognostic equations which permit the making of forecasts of the yield of winter wheat with great confidence both for individual fields and also on the scale of oblasts, regions, and republics, and for the country as a whole.

The following equation was obtained for the calculation of yield from particular fields after resumption of growth in the spring:

$$y = -14.15 + 0.22 x_1 - 59 \cdot 10^{-5} x_1^2 + 0.03 x_2 - 10^5 x_2^2,$$

where  $y$  is the yield of winter wheat Bezostaya I in hundreds of kg/hectare;

$x_1$  is the moisture supply (mm) in the soil layer  
0-100 mm;

$x_2$  is the number of stems per  $m^2$ .

Confidence level of the equation is 90%.

In the phase of emergence of the tube the expected yield ( $y$ ) can be calculated using the average supply of available moisture ( $x_1$ ) in the soil layer from 0 to 100 mm for the period from resumption of growth to emergence of the stalk, the average air temperature for the same period ( $x_2$ ), and the number of stems per  $m^2$  ( $x_3$ ).

The equation has the form:

$$y = -12.8 + 0.29x_1 - 10^{-3}x_1^2 + 0.04x_2 - 10^5x_2^2 - 0.72x_3 + 0.03x_3^2.$$

Confidence level of the equation is 82%.

There are other equations for this phase with confidence levels of 82 to 87%.

For a forecast of the yield prepared in the flowering phase, 4 equations are calculated, in which appear as mandatory predictors the supply of available moisture in the soil layer from 0 to 100 mm and the number of stems, and also other corrective factors.

For the forecast of the yield in a territory of an oblast (region) of a republic the following equation is obtained:

$$y = -19.13 + 0.32w - 10^{-4} \cdot 8w^2 + 0.02c - 10^{-6} \cdot 6c^2 - 0.06p_v + 0.0009p_v^2 + 0.02p_{vi} + 0.00007p_{vi}^2,$$

where  $y$  is the average size of yield in hundreds of kg/hectare;

$w$  is the supply of available moisture in spring in the soil layer 0-100 mm:

$c$  is the number of stems per  $m^2$  in the spring;

$p_v$  is the amount of precipitation in May;

$p_{vi}$  is the amount of precipitation in June.

This equation takes into account the actual moisture supply and the number of stems in the spring. If this forecast is given as an outlook in April, then the data on precipitation are taken from the weather forecast for May and the seasonal forecast for June or from climatological data. If the forecast is made in the flowering phase from the end of May to the beginning of June, then the precipitation for June is indicated on the basis of the weather forecast. The equation presented has a confidence level of 83%. The use as predictors of data on expected precipitation from the weather forecast is essential, especially in dry years, although in such a case verification of the crop forecast depends (by 10 to 15%) on verification of the precipitation forecast for June.

In the analysis of the coherence of yield of kernels of corn with agrometeorological factors in the matrix of correlation ratios (Yu. I. Chirkov, 1966, 1969), the largest values of correlation ratio related the yield to the



area of leafy surface ( $\eta = 0.84$ ), the height of the plants ( $\eta = 0.72$ ), the supply of available moisture in the soil layer from 0 to 50 cm ( $\eta = 0.67$  to  $0.74$ ), the total precipitation for the phase from formation of the panicle to waxy ripeness ( $\eta = 0.59$ ), and the average air temperature for the same period ( $\eta = 0.52$ ).

As is evident both for corn and for winter wheat, the closest connection of yield is with indicators characterizing the state of the crop (square of the leafy surface for corn, the number of stems per unit area of crop for winter wheat); second closest is the connection of yield with height of plants. So the significant coherence of yield with the factor mentioned is entirely regular. Measurements in the actual development phase characterize the degree of favorableness of meteorological conditions in the foregoing period and to a significant degree they predetermine maturation of the crop in the subsequent period. It must be noted that the area of leafy surface is an indicator of the photosynthetic potential of the crop, but the dynamics of its growth is an important diagnostic indicator of the condition of the planting, reflecting the influence of the whole complex of meteorological conditions on the maturation of the crop. The use of these indicators as predictors significantly increases the confidence level of the crop forecast.

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The supply of available soil moisture stands third in closeness of relation with the yield both for wheat and for corn. But in the arid light-colored soil zone it is essentially the chief agrometeorological factor, determining the area of the blades and the height of the plants and the number of ear-bearing stems.

The relation of yield with supply of soil moisture is

closer than with precipitation, because the degree of utilization of rainfall by vegetation varies significantly dependent on the character of the rainfall, the nature of the soil, land relief, and a number of other factors.

The forecast of the yield of kernels of corn is based on equations which include: the magnitude of the area of leafy surface ( $s$ ) in thousands of  $m^2$ /hectare; the supply of available moisture (mm) in the soil layer of 0 to 50 cm ( $w$ ); the air temperature in the period of formation of components; the productivity of cobs in stages IV-V of organogenesis ( $t_1$ ); and the air temperature during the month following formation of the panicle ( $t_2$ ), when flowering and pollination of the spadix and the formation of grain take place.

In practice a system of equations is used for advance information about the corn crop, which are designed for various magnitudes of area of leafy surface in the phase of formation of the panicle.

Generally this equation has the form:

$$y_s = \frac{(-aw^2 + bw - c) Kt_2}{Kt_2 w}$$

where  $y_s$  is the yield in hundreds of kg/hectare for a given area of leafy surface( $s$ );

$w$  is the supply of available moisture (mm) in the soil of 0 to 100 cm.

The coefficients  $a$ ,  $b$ ,  $c$  depend on the amount of leafy surface ( $s$ ) in thousands of  $m^2$ /hectare.

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For example, for 30,  $a = -0.0071$ ,  $b = +1.41$ ,  $c = -3.2$ ;  
 20,  $a = -0.006$ ,  $b = +1.1$ ,  $c = -4.2$ ;  
 10,  $a = -0.0029$ ,  $b = +0.53$ ,  $c = -1.5$ .

A graph of these equations is provided for practical use. The coefficient  $Kt_2$  is taken from the table

TABLE  
 CORRECTION FACTOR FOR TEMPERATURE DURING THE  
 MONTH FOLLOWING APPEARANCE OF THE PINACLE

Supply of Available Moisture	Average Air Temperature for the Period (deg)				
	16	18	20	22	24
100	0.68	0.86	0.97	1.00	0.96
80	0.72	0.88	0.99	0.98	0.90
60	0.78	0.90	1.00	0.93	0.80
40	0.84	0.93	0.97	0.86	0.65
20	0.90	0.92	0.90	0.80	0.50

The coefficient  $Kt_1w$  is calculated for average air temperature above 20 and soil moistness below 50 mm by the equation:

$$Kt_1w = 0.065t_1 - 0.016w + 0.46$$

where:  $t_1$  is the average air temperature during stages IV-VI of organogenesis of the cob;

$w$  is the average moisture supply for the same period.

Thermal conditions are considered in the previously mentioned prognostic equations as correction factors, but with high temperature and inadequate moistening the reduction in crop can be considerable. Air temperature, as accounted for in the coefficient  $Kt_1w$ , is an observed quantity. Temperature of the phase following appearance of the panicle ( $Kt_2$ ) is a

quantity given in the monthly weather forecast, the verification of which is comparatively low. Therefore, at the same time that the yield is evaluated using the temperature forecast,  $Kt_2$  is also computed according to climatological data with probabilities of occurrence of 20, 50, and 80%, thus giving 3 levels of expected yield which serve as a "bracket" for the forecast.

The tendencies and increase in yield are observed in connection with improvement of the level of agricultural technology, other conditions being equal.

The numerical value of this quantity is variable for particular agricultural regions and on the average can in one year amount to 5 - 10%. This quantity (trend) is considered in the equation, and is introduced into the forecast scheme as a correction factor.

Inclusion of the effect of fertilization as a predictor in the prognostic equations has the greatest significance in regions where the soils provide low natural fertility (light-colored soil zone). For a winter wheat crop in this zone one must account for the influence of agrometeorological conditions on the effectiveness of mineral fertilizers. In early spring in podzolic clayey soils an intense intra-soil drainage occurs because of excess water, which brings about a loss of nitrogen from the soil. Thus the effect on the yield of an early spring dressing of nitrogen fertilizer depends on the surplus of soil moisture. According to the data of M. S. Kulik (1971) on the supply of soil moisture in the layer of 0 to 50 cm, at 40 to 60 mm beyond field capacity the effectiveness of top dressing increases by 100 kg/hectare, and for an excess of moisture greater than 60m [sic], by 200 kg/hectare.

The principal cause of the varying effectiveness of a top dressing of nitrogen fertilizer in the spring is the non-uniformity in the length of the period between resumption of growth in the spring and the rise of the average daily temperature above  $10^{\circ}$ . In this phase winter wheat passes through stage IV of organogenesis, which determines the spikelet tubercles in the ear. The higher the temperature in this period, the (according to Kulik's data) faster stage IV is completed and the effect of fertilization is reduced, as given by the following equation:

$$y = 0.15x + 0.29; r = 0.91, S_y = \pm 0.21 \text{ hundreds of kg/hectare}$$

where  $y$  is the increase in crop (hundreds of kg/hectare);

$x$  is the number of days with average daily temperature between  $5$  and  $10^{\circ}$ .

This equation is used in the spring for refinement of the forecast of winter wheat crop.

For spring wheat, grown mostly in a zone of inadequate and unstable moistness, the governing predictors are the moisture indicators. A. V. Protserov and K. V. Kirilicheva offered some equations obtained for this crop forecast. For example, for the variety Skala, distributed in eastern and frequently in western Siberia, the equation has the form:

$$y = 0.090V_2 + 1.840x_5 + 0.012x_2 - 16.824. K = 0.78$$

where:

$V_2[\text{sic}]$  is the provision of moisture (%) in the period from emergence of the stalk to flowering;

$x_5^5[\text{sic}]$  is the number of developed spikelets per ear in the flowering phase;

$x_2^2[\text{sic}]$  is the number of stems per  $\text{m}^2$  in the phase of emergence into a tube.

With the examples of winter and spring wheat and of corn, the scientific bases of methods of crop forecasting have been worked out. Methods of selection of predictors, the forms of the prognostic equations, and various ways of revising the forecast<sup>t</sup> have been presented.

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In the USSR all crop forecasts are prepared according to a single scheme, which includes 3 essential steps.

- 1) Collection of agrometeorological data with a network of observational stations which carry out special air and surface examinations of the crop, critical control of the information obtained, and its processing by ECM.
- 2) Estimation of initial conditions on the basis of the information obtained, i.e., a record of the combined agrometeorological conditions of germination and development and characterization of the condition of the crop on the date of preparation of the forecast.
- 3) Calculation of the expected yield by means of the basic prognostic equations starting from the evaluated initial conditions, adjustment of the results on the basis on the intensity of effect of various factors.

It should be noted that many mathematical models generated in the USSR and abroad, which endeavor to describe the complex process of crop maturation with the help of an accounting of many factors including physiological processes, stereometry of the crop, the details of transpiration, the energetics of photosynthesis, and the activity of soil microflora, as yet are not practicable for forecasting the crop under working conditions on the scale of millions of hectares. The basic reason

is the impossibility of arranging observations for the specified complicated processes and properties in a routine network of meteorological stations. A second reason is the operational character of forecast preparation, which presupposes as far as possible the simplest, least laborious form of calculation, allowing the processing of the huge amount of data even from a limited number of predictors.

That is why existing methods are in practice successfully applied, based on the statistical reduction of a large stock of related observations, with an indispensable biological and physical background for the selection of predictors.

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Verification of crop forecasts is derived from comparison of predicted with actual yields using certain statistical tools. The average score for a 10-year period for the crops mentioned comes out to be 90 to 92%.

Further improvement of existing methods of crop forecasting requires a more detailed initial condition and primarily an accounting of the regularities of the spatial distribution of factors entering into the prognostic equations. Increasing the timeliness of crop forecasts has great significance, and, for this purpose, factors and processes are used which have a greater time lag than the variable weather conditions (soil moisture supply, the developed photosynthetic potential of the crops, etc.). Nevertheless broader utilization of climatological characteristics taking into account periodic fluctuations of the climate is promising. It is essential to consider as correction factors the detrimental effects of phytopathological and entomological particulars which in turn are related to weather conditions. International collaboration of agrometeorologists will promote the

swifter improvement of existing methods of crop forecasting and the development of methods for many other agricultural cultures. This will be a contribution by agrometeorologists to raising the productivity of world agriculture.